Ibitira: A basaltic achondrite from a distinct parent asteroid

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Abstract─I have done detailed petrologic study of Ibitira, nominally classified as a basaltic eucrite. The Fe/Mn ratio of Ibitira pyroxenes with <10 mole % wollastonite component is 36.4±0.4, and is well-resolved from those of five basaltic eucrites studied for comparison; 31.2-32.2. Data for the latter completely overlap. Ibitira pyroxenes have lower Fe/Mg than the basaltic eucrite pyroxenes. Thus, the higher Fe/Mn ratio does not reflect a simple difference in oxidation state. Ibitira also has an oxygen isotopic composition, alkali element contents and a Ti/Hf ratio that distinguish it from basaltic eucrites. These differences support derivation from a distinct parent asteroid. Ibitira is the first recognized representative of the fifth known asteroidal basaltic crust.

INTRODUCTION

Eucrites are pigeonite-plagioclase basalts that are grouped with diogenites (coarse-grained orthopyroxenites) and howardites (polymict breccias of basalts, gabbros and orthopyroxenites) into the HED clan of achondrites. These compose the largest suite of crustal rocks available from a differentiated asteroid, often equated with 4 Vesta (Drake, 2001). Pristine mafic clasts from mesosiderites are virtually indistinguishable from HEDs, but because of their very different post-crust-formation history, mesosiderites likely were formed on a different parent asteroid (Mittlefehldt et al., 1998). The angrite group (olivine-diopside-anorthite basalts) is a much smaller suite, with compositional characteristics demonstrating a distinct formational history and parent asteroid (Mittlefehldt et al., 1998). Northwest Africa (NWA) 011 is a pigeonite-augite-plagioclase basalt; the sole representative of a fourth, differentiated asteroid crust (Yamaguchi et al., 2002). Basaltic achondrites are manifestations of one or more early, intense heat sources that were capable of rapidly bringing asteroid-sized bodies to igneous temperatures. Studies of these materials provide evidence on the nature of the early heat source(s) and the igneous evolution of their parent bodies.

This study was prompted by recent high precision oxygen-isotope data on a suite of HED meteorites (Wiechert et al., 2004) which showed that Ibitira deviated from a mass-dependent fractionation line defined by other HEDs (Fig. 1a). HED meteorites display a very restricted range in $\Delta^{17}O'$, which indicates derivation from a homogeneous oxygen reservoir subject only to mass-dependent isotopic fractionation (Fig. 1b). (The oxygen-isotope terminology used here follows that of Wiechert et al., 2004.) In contrast, replicate analyses of Ibitira were displaced from other HEDs by roughly 16 times the 1σ analytical uncertainty (Wiechert et al., 2004). To further investigate the relationship of Ibitira to HEDs, I have done electron microprobe analyses

of phases in it and representative basaltic eucrites. Here I report mineral compositional data and discuss literature bulk rock compositional data for Ibitira, nominally classified as a eucrite, which support derivation of this basaltic achondrite from a parent asteroid distinct from that of the HED clan.

SAMPLES AND ANALYTICAL METHODS

A thin section of Ibitira was made for this study by the US National Museum of Natural History (Smithsonian Institution.) For comparative purposes, six basaltic eucrites were studied. Until recently, Ibitira was unique as the only unbrecciated, metamorphosed basaltic eucrite (Gomes and Keil, 1980; Steele and Smith, 1976; Wilkening and Anders, 1975). Bates Nunataks (BTN) 00300, Elephant Moraine (EET) 90020 and Graves Nunataks (GRA) 98098 are unbrecciated and metamorphosed basaltic eucrites with petrologic similarities to Ibitira. Sioux County and Stannern are classic brecciated basaltic eucrites representative of the main-group and Stannern-trend (Stolper, 1977). The Sioux County thin section was made from basalt clasts hand-picked from a sample obtained from the British Museum (Natural History). Yamato (Y) 793164 is classified as a eucrite but has been paired with polymict eucrite Y-792769 based on texture, noble gas contents and cosmic-ray exposure and terrestrial residence ages (Miura et al., 1993; Takeda, 1991). The sample studied here is believed to be a clast from the pairing group, and is a metamorphosed, ferroan basalt representative of evolved, Nuevo Laredo-trend basaltic eucrites (Mittlefehldt and Lindstrom, 1993).

The electron microprobe analyses for all but Y-793164 were done using the Cameca SX100 electron microprobe at NASA Johnson Space Center. Y-793164 was analyzed using our previous microprobe, a Cameca CAMBAX. Analytical conditions were 20 kV, 40 nA, 1 µm

beam for pyroxene, chromite and ilmenite, and 15 kV, 20 nA, 1 μm beam for plagioclase. A key parameter evaluated in this study is the Fe/Mn ratio of pyroxene. For eucrite pyroxene analyses, the analytical conditions yield 1σ counting uncertainties on Fe/Mn of ±0.76%. Total uncertainty on the precision can be estimated from the 1σ standard deviation of the mean of ratios, ±1.2%. All meteorites were analyzed using the same analytical conditions, though at different times over several years. The total uncertainty is a good measure for comparing the data sets.

RESULTS

Averages for low-Ca and high-Ca pyroxene for Ibitira are given in Table 1, average oxide analyses in Table 2, and average plagioclase analyses in Table 3. Figure 2a compares molar Fe/Mn for low-Ca pyroxene (<10 mole % wollastonite component) analyses between Ibitira and five basaltic eucrites, exclusive of ferroan Y-793164. The Ibitira data are well resolved from those of the five basaltic eucrites, while the data for the latter completely overlap. When all analyses are considered irrespective of Ca content, the data distributions are still well resolved, with almost no overlap in ratios (Fig. 2b). Comparing Fe/Mn vs. Fe/Mg for analyses with the lowest Ca contents, Ibitira has a higher Fe/Mn at lower Fe/Mg than the basaltic eucrites (Fig. 2c). (The Fe/Mg ratio of eucritic pyroxenes is inversely correlated with Ca content. To obtain comparable averages for Fig. 2c, only analyses within 2 mole % wollastonite component of the most Ca-poor analysis were averaged.)

DISCUSSION

Ibitira has long been noted for having unusual characteristics. It contains abundant vesicles (Wilkening and Anders, 1975), which are rare in HEDs (Mittlefehldt et al., 1998). It is unbrecciated with a fine-grained, hornfels-texture (Steel and Smith, 1976), that until recently

was unique among HEDs. Plagioclase in Ibitira is unusually calcic, An_{95} (Steele and Smith, 1976; Wilkening and Anders, 1975; Table 3), compared to those found in basaltic eucrites; An_{75-93} (Mittlefehldt et al., 1998; Papike, 1998). This is an expression of the low alkali element content of Ibitira compared to HED basalts (Stolper, 1977). These atypical characteristics, coupled with the recent oxygen isotopic distinction (Wiechert et al., 2004), led me to question whether Ibitira was a basaltic eucrite *sensu stricto*.

Oxygen isotopic compositions are but one means to distinguish the heritage of planetary basalts; Fe/Mn ratios are also diagnostic (Papike, 1998). Ferrous iron and Mn^{2+} are homologous cations; they have very similar ionic radii (78 vs. 83 pm, Lodders and Fegley, 1998) and are inefficiently fractionated in mafic igneous systems (Stolper, 1977). However, Mn is almost strictly divalent in typical igneous systems, while Fe can be in valence states of 0, 2+, and/or 3+ depending on oxygen fugacity, and Fe more readily forms sulfides. Manganese is a moderately volatile element and was fractionated from Fe by nebular processes; bulk chondrite Fe/Mn ratios vary by a factor of 2 (Lodders and Fegley, 1998). Thus, parent bodies can have quite different Fe/Mn and this will be reflected in their basalts (Papike, 1998).

In basaltic achondrites, pyroxene contains the bulk of the whole rock Fe and Mn. Among low-Ca pyroxene (<10 mole % wollastonite component) analyses, there is no overlap in Fe/Mn ratios between Ibitira and five representative basaltic eucrites (Fig. 2a). When all analyses are considered irrespective of Ca content, the data distributions are still well resolved, with almost no overlap in ratios (Fig. 2b). The data from the five basaltic eucrites completely overlap (Fig. 2a, b). The higher Fe/Mn ratio for Ibitira could simply indicate a slightly higher oxidation state for this basalt, rather than a fundamental difference in its source or petrologic evolution. However, higher oxidation state would also result in higher Fe/Mg. Ibitira has lower molar

Fe/Mg in its low-Ca pyroxenes (Fig. 2c) compared to those of the five basaltic eucrites studied here. Thus, the difference between Ibitira and basaltic eucrites is inconsistent with simple redox variations.

Other geochemical characteristics distinguish Ibitira from basaltic eucrites. Ibitira is anomalously depleted in alkali elements (Stolper, 1977), and also is enriched in Ti compared to other incompatible refractory lithophile trace elements. Ibitira is well resolved from basaltic eucrites, angrites, NWA 011 and basalt clasts from mesosiderites on a plot of $(Ti/Hf)_{CI}$ vs. $(Na/Ca)_{CI}$ (Fig. 3). On this diagram, NWA 011 is indistinguishable from basaltic eucrites, but it is very different in O isotopic composition and Fe/Mn (Yamaguchi et al., 2002). Angrites are well separated from basaltic eucrites in Na/Ca, and have distinct Fe/Mn (Mittlefehldt et al., 1998) and O isotopic compositions (Franchi and Greenwood, 2004). Curiously, Ibitira and angrites are indistinguishable in O isotopic composition (Franchi and Greenwood, 2004), although they are distinct in Na/Ca and Fe/Mn. Primary basalt clasts from mesosiderites (Rubin and Mittlefehldt, 1992) are not distinguishable from basaltic eucrites based on available data (Fig. 3).

There are two basic models for petrologic evolution of the HED parent asteroid: (i) basaltic eucrites represent residual melts from crystallization of a totally molten asteroid (Righter and Drake, 1997; Ruzicka et al., 1997), or (ii) they are partial melts of a partially melted asteroid (Stolper, 1977). In the former case, silicate material initially would have been well mixed, and oxygen isotopic, Fe/Mn, Ti/Hf and Na/Ca ratios should be uniform. Crystallization of the molten asteroid will not alter the $\Delta^{17}O'$ of the melt, while Fe/Mn will slightly decrease during olivine crystallization, and then slightly increase when pyroxene becomes the major crystallizing phase (Stolper, 1977). Titanium and Hf are incompatible elements, and the Ti/Hf will decrease

slightly with solidification as Hf will be slightly more incompatible owing to its larger ionic radius (83 vs. 60 pm, Lodders and Fegley, 1998). The Na/Ca ratio will slightly increase with pyroxene and plagioclase crystallization; a crystallization model for the HED parent asteroid calculates only a 50% increase in Na/Ca by 85% solidification (Righter and Drake, 1997). The average Na/Ca ratio for basaltic eucrites is 2.5 times that of Ibitira. The differences in composition between Ibitira and basaltic eucrites (Figs. 1-3) are inconsistent with formation on a single, once molten body, and would indicate distinct parent-asteroid sources if this is the correct model for eucrite petrogenesis.

The case is not as clear if eucrites were formed by partial melting. In principle, a heterogeneous parent asteroid could produce a suite of basalts that differ in these compositional parameters. For example, ureilites are generally considered to be partial-melt residues and to come from a single parent asteroid (Mittlefehldt et al., 1998), yet they exhibit substantial ranges in oxygen isotopic composition (Clayton and Mayeda, 1996) and molar Fe/Mn (Mittlefehldt et al., 1998). If individual basalt flows represent partial melts of limited regions of their parent asteroid that did not completely mix or equilibrate with other material during ascent and eruption, then isotopic and chemical heterogeneities could be partially preserved. Note that ureilites show a positive correlation between Fe/Mn and Fe/Mg (Mittlefehldt et al., 1998), contrary to the difference between Ibitira and basaltic eucrites (Fig. 2c).

Wiechert et al. (2004) recognized that Ibitira could be from a distinct parent asteroid, but argued in favor of derivation from a heterogeneous HED parent asteroid. Based on Figures 1-3, Ibitira would have to be the sole representative of a source region that produced basalts with distinct oxygen isotopic composition, slightly higher mg#, higher Fe/Mn, a depletion in alkali

elements, and a higher Ti/Hf ratio. The simpler explanation is that Ibitira was derived from a distinct parent asteroid.

Support for this position comes from the cosmic-ray exposure record of HEDs, which shows at least three significant age clusters indicating separate impact events that liberated the majority of HED meteorites (Eugster and Michel, 1995; Welten et al., 1997). The high precision oxygen isotopic data for HEDs cover most of the cosmic-ray exposure age range, including the three age clusters.

There are two interpretations of the cosmic-ray exposure age clusters. The first is that they represent three separate launch events from random regions of the parent asteroid (Eugster and Michel, 1995; Welten et al., 1997). This interpretation implies that the "normal" oxygen isotopic reservoir is widespread and dominates on the HED parent asteroid. Ibitira is unlikely to have originated on the HED parent asteroid if this interpretation is correct.

The second interpretation is that the clusters date the breakup of multi-kilometer spalls from the parent asteroid (Migliorini et al., 1997). These spalls could have been derived from a single, basin-forming impact on the parent asteroid, and thus represent one extensive region of the crust. The common interpretation is that these spalls were derived from the southern basin on 4 Vesta (Thomas et al., 1997) that covers roughly 15% of the surface. This would more easily allow for anomalous basalts like Ibitira to have existed on the HED parent asteroid; it could have been ejected from a distant region of 4 Vesta by a smaller impact.

Among the HED samples analyzed are several polymict breccias, and these have oxygen isotopic compositions like those of diogenites, cumulate eucrites and basaltic eucrites (Wiechert et al., 2004). Howardites are regolith samples of the HED asteroid. Regolith formation on

asteroids involves widespread mixing over the surface (Housen et al., 1979). If oxygen isotopic heterogeneity of the magnitude demonstrated by Ibitira (16 times the 1σ analytical uncertainty) was common on the HED surface when regolith formation occurred, howardites ought to be notably more heterogeneous than HED monomict breccias. This is not observed (Wiechert et al., 2004). Actually, howardites are slightly enriched in ^{16}O compared to basaltic eucrites due to inclusion of a small amount of CM and CR chondrite debris (Wiechert et al., 2004; Zolensky et al., 1996; see Fig. 1b). Wiechert et al. (2004) noted that polymict eucrite ALHA78132 is depleted in ^{16}O compared to HEDs. However, paired polymict eucrite ALHA76005 is ^{16}O-enriched, and the average $\Delta^{17}O'$ ratio for them is identical to the HED mean. Whether this reflects real isotopic heterogeneity of the meteorite should be addressed.

Wiechert et al. (2004) also found that two basaltic eucrites are depleted in ^{16}O relative to the HED mean. A single analysis of Caldera is discrepant by 3σ, while duplicate analyses of Pasamonte are displaced by an average of 4σ (Fig. 1b). Caldera is a coarse grained, unbrecciated basaltic eucrite (Boctor et al., 1994). Pasamonte is a basaltic eucrite that was only relatively recently recognized as have polymict character (Metzler et al., 1995). The data for these two eucrites suggest that oxygen isotopic heterogeneity on the order of 3-4 times the current analytical precision may exist on the HED parent body. Nevertheless, the relative isotopic uniformity of the howardites argues against Ibitira-like terranes being common on the HED parent body.

On balance, the simplest explanation for the oxygen isotopic, pyroxene composition, bulk composition, and cosmic-ray exposure data for Ibitira and HEDs is that the former was derived from a distinct parent asteroid. By virtue of Ockham's razor, this is the more plausible explanation.

Meibom and Clark (1999) estimated the number of asteroids represented in the meteorite collection at about 135, with the largest fraction of these being represented by irons. Most irons are core fragments of differentiated asteroids (Mittlefehldt et al., 1998), and basaltic crusts should therefore have been common in some portion of the asteroid belt. Based on the arguments put forth above, five of these crusts have been sampled, viz. HEDs, mesosiderite silicates, angrites, NWA 011 and Ibitira. Of these, NWA 011 stands out as having a very different oxygen isotopic composition, similar to that of CR chondrites (Yamaguchi et al., 2002), and likely was derived from a region of the asteroid belt distant from the other four parent asteroids. The other four sampled crusts have very similar oxygen isotopic compositions, suggesting their parent asteroids accreted material from a more limited region of the nebula. The angrites are quite different in Fe/Mn, Na/Ca and oxidation state (Mittlefehldt et al., 1998), however.

With only one example available for study, detailed reconstruction of Ibitira's parent asteroid cannot be made. Nevertheless, the differences between Ibitira and basaltic eucrites allow some basic inferences to be made. Ibitira has concentrations of highly incompatible refractory lithophile elements similar to those of basaltic eucrites; La 2.54 µg/g vs. 2.56 µg/g for Juvinas for example. Neither is depleted in Eu relative to Sm indicating plagioclase fractionation did not affect their compositions. Thus, to first order, Ibitira and Juvinas represent melts from similar stages of evolution of their respective parent asteroids. Ibitira has a more magnesian composition evidenced in pyroxene (Fig. 2c) and bulk rock compositions (mg# 41.4 vs. 40.5 for Juvinas), suggesting its parent asteroid has a slightly higher mg#. The higher Fe/Mn coupled with lower Fe/Mg (Fig. 2c) suggests depletion in moderately volatile Mn, which is also indicated by the low alkali element content of Ibitira (Fig. 3). More detailed comparisons will

require identification of additional samples from the Ibitira parent asteroid - these may already exist in the collection of poorly characterized eucrites.

The discovery of small, V-class asteroids dynamically associated with 4 Vesta, the so-called vestoids, strengthened the case for identifying 4 Vesta as the HED parent asteroid (Binzel and Xu, 1993). Evidence is accumulating, however, that the vestoids may actually represent fragments from more than a single differentiated asteroid (Sykes and Vilas, 2001; Florczak et al., 2002). Because differences between Ibitira and basaltic eucrites are small, their parent asteroids likely were formed within a limited region of the belt. This is consistent with the emerging astronomical evidence on vestoids.

The mesosiderite parent asteroid also ought to be within the same region of the belt by virtue of the very similar compositional characteristics of the basalt suites (Fig. 3). If the high metal content of mesosiderites is typical of the surface of their parent asteroid, it will have very different spectroscopic characteristics from the vestoids. Some S-class asteroids of the Agnia (radius 14 km) and Merxia (radius 16 km) families have reflectance spectra consistent with mafic silicates, but with subdued absorption features suggestive of a high abundance of opaque material (Sunshine et al., 2004). One candidate for this opaque material is metal, and thus these asteroids are potential crust fragments of the mesosiderite parent asteroid (Sunshine et al., 2004).

The Dawn mission, scheduled for launch in June-July 2006, will orbit 4 Vesta for 7 months starting in October 2011 (Russell et al., 2004). The data return will include full surface imagery, spectrometry mapping in visible and infra-red bands, and abundances of H, O, Mg, Al, Si, K, Ca, Ti, Fe, Sm, Gd, Th and U. Spectroscopic data on HED meteorites are being collected as “ground truth” for comparison with spacecraft acquired data, and a vast body of compositional data exists for HEDs. The mineralogical and chemical distinctions between Ibitira and basaltic

eucrites are subtle. This will pose a challenge for investigators attempting to distinguish geologic terranes on 4 Vesta, or equate specific basaltic achondrites with the vestan crust, based on spacecraft data.

The low alkali element contents of Ibitira offer one opportunity to distinguish it from basaltic eucrites from 4 Vesta orbit. Ibitira has a lower K content than do basaltic eucrites (Stolper, 1977). However, the K contents of the latter scatter more than do the Na contents (Mittlefehldt, 1987), and distinguishing Ibitira-like basalts from HED-like basalts will be difficult based on K. Figure 4 shows K vs. Mg and K vs. Ti for Ibitira and HEDs. Ibitira lies at the low K end of the basaltic eucrite continuum, and Ibitira-like terranes on 4 Vesta may simply appear to be K-poor basaltic eucrite-like terranes on 4 Vesta. Ibitira has a higher Ti content relative to other refractory incompatible elements compared to basaltic eucrites (Fig. 3), and stands out on K vs. Ti and Sm vs. Ti plots (Fig. 4). However, Ti measurement errors expected for the Dawn mission are substantial (Russell et al., 2004; no error estimates were given for Sm) and data from Ibitira-like terranes will overlap those from basaltic eucrite-like terranes (Fig. 4).

A reflectance spectrum of Ibitira determined at the Brown University Keck/NASA Reflectance Laboratory (Relab) is distinct from those of most basaltic and cumulate eucrites determined under identical experimental conditions (Fig. 5). However, portions of individual eucrite spectra can closely match the Ibitira spectrum. Thus, Moore County (cumulate eucrite) is similar to Ibitira in the region of the 0.9 μm pyroxene absorption feature, while Cachari (basaltic eucrite) is a close match from ~0.81 to 1.74 μm. Binzel et al. (1997) showed that spectra of 4 Vesta (52 km/pixel resolution) have 0.9 μm pyroxene absorption features that display a range of depths and widths, which they used to demonstrate geological heterogeneity of the surface. Figure 6 is a plot of depth vs. width of the 0.9 μm pyroxene absorption feature of Relab spectra

of Ibitira and several HEDs. Ibitira has a deeper and wider feature than do basaltic eucrites measured under identical conditions. However, some cumulate eucrites are similar to Ibitira in the shape of the 0.9 µm pyroxene absorption feature. (Some diogenites are similar as well, but presumably the lack of a plagioclase absorption feature would allow them to be distinguished from Ibitira-like basalts.)

The discussion of spectra above was based on "ideal" spectra – spectra taken under controlled conditions on carefully prepared samples of igneous lithologies. The vestan surface won't be so accommodating. The surface will be covered with regolith of mixed fragmental debris unsorted by size, and space weathering will have altered the spectral properties. Combining chemical and spectroscopic data will allow inferences regarding the types of igneous materials in the vestan crust. Nevertheless, it will be a challenge to distinguish basalt types as similar as Ibitira and basaltic eucrites from vestan orbit.

CONCLUSIONS

The mean Fe/Mn ratio of low-Ca pyroxene (<10 mole % wo) in Ibitira is 36.4±0.4 (1σ standard error of the mean), and is well-resolved from those of five basaltic eucrites studied for comparison; 31.2-32.2. The Fe/Mn ratios for the latter completely overlap. Ibitira pyroxenes also have lower Fe/Mg (1.42±0.03) than those of the basaltic eucrites (1.57-1.73). Thus, the higher Fe/Mn ratio does not reflect a simple difference in oxidation state. Rather, a more magnesian source slightly depleted in Mn for Ibitira is more plausible. Ibitira also has an oxygen isotopic composition (Wiechert et al., 2004), alkali element contents (Stolper, 1977) and a Ti/Hf ratio that distinguish it from basaltic eucrites. These differences support derivation from a distinct parent asteroid. Although clearly distinct, Ibitira is nonetheless very similar to basaltic

eucrites and basaltic clasts in mesosiderites in chemical and isotopic composition. This suggests the parent asteroid for Ibitira was formed within the same limited region of the asteroid belt as those of the latter.

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Table 1. Average analyses of representative pyroxenes for Ibitira.

	pigeonite				augite
type	host	host	lamella†	lamella	host‡
n*	8	10	3	10	13
SiO_2	48.9	48.9	49.0	48.4	49.0
TiO_2	0.40	0.59	1.10	0.94	1.10
Al_2O_3	0.35	0.44	1.54	1.08	1.36
Cr_2O_3	0.21	0.23	0.49	0.41	0.48
FeO	33.5	33.1	18.9	21.3	17.9
MnO	0.910	0.900	0.519	0.582	0.509
MgO	13.1	13.0	11.0	11.6	10.6
CaO	1.84	2.04	16.1	14.1	18.0
sum	99.210	99.200	98.649	98.412	98.949
			molar		
Fe/Mn	36.3	36.3	35.9	36.1	34.7
Fe/Mg	1.43	1.43	0.96	1.03	0.95
mg#	41.1	41.2	50.9	49.3	51.4
wo	4.0	4.4	34.9	30.1	38.5
en	39.4	39.4	33.2	34.4	31.6
fs	56.6	56.2	32.0	35.5	29.9
			atoms per 6 oxygens		
Si	1.9618	1.9593	1.9234	1.9192	1.9201
Ti	0.0121	0.0178	0.0325	0.0280	0.0324
Al	0.0166	0.0208	0.0713	0.0505	0.0628
Cr	0.0067	0.0073	0.0152	0.0129	0.0149
Fe	1.1240	1.1092	0.6205	0.7063	0.5866
Mn	0.0309	0.0305	0.0173	0.0196	0.0169
Mg	0.7834	0.7765	0.6437	0.6857	0.6192
Ca	0.0791	0.0876	0.6772	0.5991	0.7558
sum	4.0146	4.0090	4.0011	4.0213	4.0087

*Number of analyses averaged. †Three most Ca-rich lamella analyses from three pigeonite hosts. ‡Thirteen most Ca-rich analyses from four augite hosts.

Table 2. Average analyses of representative ilmenite and ulvöspinel grains for Ibitira.

	ilmenite		ulvospinel	
n*	7	3	5	5
TiO_2	53.2	52.8	21.6	23.1
SiO_2	0.04	0.03	-	-
Cr_2O_3	0.19	0.66	20.8	19.0
Al_2O_3	0.02	0.02	4.35	3.78
V_2O_3	-	-	0.100	0.094
FeO	43.2	43.6	50.2	51.2
MnO	0.680	0.609	0.533	0.532
MgO	1.26	1.12	1.01	0.98
CaO	0.02	-	0.01	0.01
sum	98.610	98.839	98.603	98.696
molar				
Fe/Mn	62.7	70.7	93.0	95.0
mg#	4.94	4.38	3.46	3.30
cr#	-	-	76.2	77.1
atoms per 3 oxygens (ilmenite) or 4 oxygens (spinel)				
Ti	1.0089	1.0015	0.5966	0.6386
Si	0.0010	0.0008	-	-
Cr	0.0038	0.0132	0.6040	0.5522
Al	0.0006	0.0006	0.1883	0.1638
V	-	-	0.0029	0.0028
Fe	0.9111	0.9197	1.5418	1.5740
Mn	0.0145	0.0130	0.0166	0.0166
Mg	0.0474	0.0421	0.0553	0.0537
Ca	0.0005	-	0.0004	0.0004
sum	1.9878	1.9909	3.0059	3.0021

* Number of analyses averaged. A "-" indicates below detection limit, or not calculated.

Table 3. Average analyses of representative plagioclase grains for Ibitira.

n*	5	5	5
SiO_2	44.2	44.1	43.7
Al_2O_3	36.0	36.1	36.0
FeO	0.22	0.41	0.29
MgO	0.041	0.031	0.035
CaO	19.2	19.1	19.2
Na_2O	0.53	0.53	0.48
K_2O	0.048	0.046	0.043
sum	100.239	100.317	99.748
	mole %		
an	95.0	94.9	95.4
ab	4.7	4.8	4.3
or	0.3	0.3	0.3
	atoms per 8 oxygens		
Si	2.0391	2.0343	2.0277
Al	1.9576	1.9629	1.9689
Fe	0.0085	0.0158	0.0113
Mg	0.0028	0.0021	0.0024
Ca	0.9491	0.9441	0.9546
Na	0.0474	0.0474	0.0432
K	0.0028	0.0027	0.0025
sum	5.0073	5.0093	5.0106

*Number of analyses averaged.

FIGURE CAPTIONS

Figure 1. Oxygen isotopic composition of Ibitira compared to HED meteorites (data from Wiechert et al., 2004). $\Delta^{17}O'$ is the deviation from the terrestrial mass-dependent fractionation line; mass-dependent fractionation on this diagram will yield horizontal data trends (Wiechert et al., 2004). The dashed line is the average $\Delta^{17}O'$ of the HED samples, exclusive of Ibitira and howardites (see text). a. Ibitira cannot be related to HED meteorites by simple chemical fractionation processes. The $\pm 2\sigma$ error bars for the Ibitira data are shown; these are typical of the analytical uncertainties (Wiechert et al., 2004). b. Expansion of the diagram showing only the HED data. Error bars ($\pm 2\sigma$) are shown for those samples that do not overlap the mean ratio. Two samples of Pasamonte (P) deviate from the mean ratio by 4σ on average, while Caldera (C) deviates by 3σ.

Figure 2, Pyroxene compositional data for Ibitira compared to several basaltic eucrites. a. Fe/Mn histogram of individual analyses with <10 mole% wollastonite component. Ibitira is completely resolved from the basaltic eucrites, while data for the latter completely overlap. b. Pyroxene compositional data for Ibitira compared to those for five basaltic eucrites. There is almost no overlap in molar Fe/Mn between Ibitira analyses and those of the basaltic eucrites, regardless of Ca content. The basaltic eucrite data completely overlap and individual samples are not distinguished. c. Fe/Mn vs. Fe/Mg for Ibitira compared to basaltic eucrites, plus a ferroan residual basalt clast (Y) from Y-793164 (Mittlefehldt and Lindstrom, 1993). The data are averages of individual analyses within 2 mole% wo of the most Ca-poor analysis.

The error bars are 1σ standard deviations of the means. Igneous fractionation would yield a slightly sloped, nearly horizontal trend on this diagram (arrow), while Fe redox will result in a positive Fe/Mn-Fe/Mg correlation. Ibitira cannot be related to the basaltic eucrites by either mechanism.

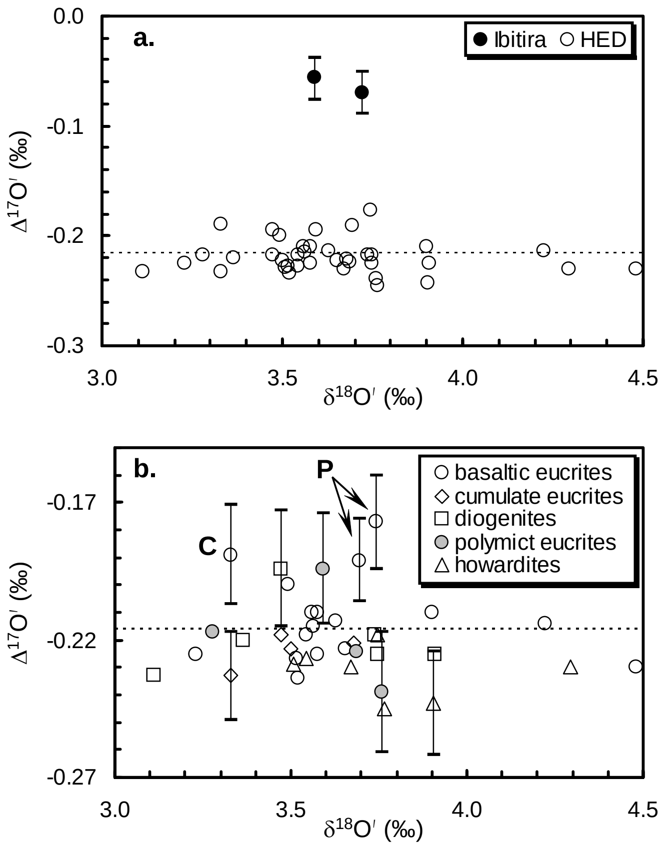
Figure 3. CI-normalized Ti/Hf vs. Na/Ca diagram comparing Ibitira to basaltic eucrites, angrites, NWA 011 and primary basaltic clasts from mesosiderites. Ibitira is distinct from any of these other asteroidal basalts. The data averages used in this figure and sources of the data are given in Appendix Tables A1 and A2.

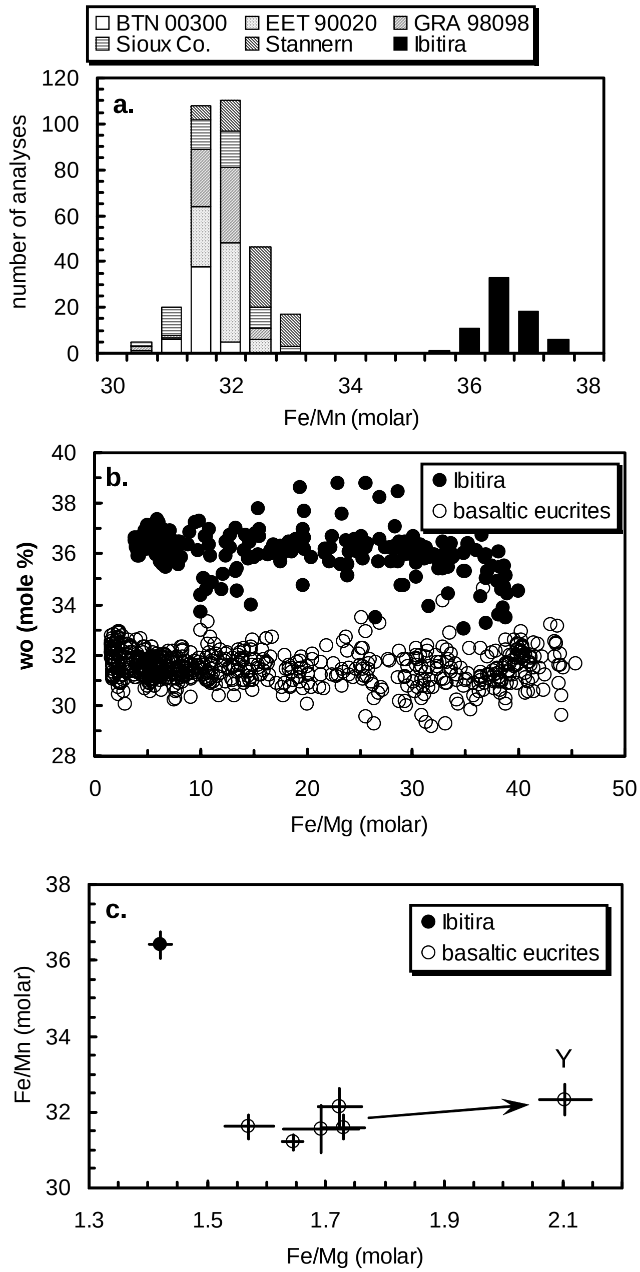
Figure 4. K vs. Mg, K vs. Ti and Sm vs. Ti for average whole rock HED meteorites compared to Ibitira. Magnesium, K, Ti and Sm are elements to be determined by the Dawn mission at 4 Vesta (Russell et al., 2004). Because Ibitira is depleted in alkali elements compared to HEDs (Stolper, 1977), K may be particularly diagnostic for comparing basaltic achondrites with the vestan crust. The error bars shown for Ibitira represent the expected uncertainties for Dawn measurements at those concentrations, and for the assumed mission plan (Russell et al., 2004). No error estimates for Sm were given. It will be challenging to distinguish Ibitira from some basaltic eucrites.

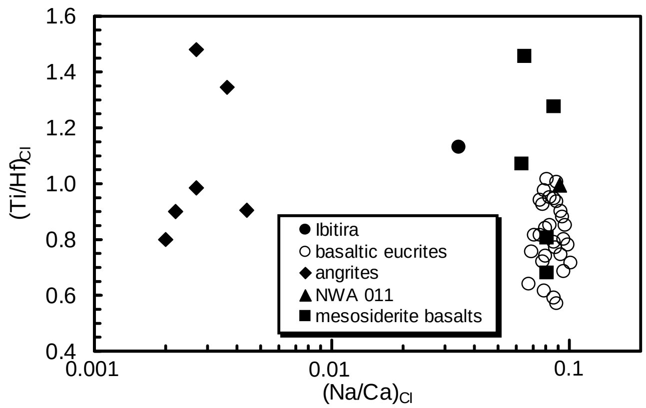
Figure 5. Comparison of the reflectance spectrum of Ibitira with those of several basaltic and cumulate eucrites. If the basaltic eucrites shown are representative of the suite as a whole, then it may be possible to distinguish between them and Ibitira-like basalts on 4 Vesta. None of the basaltic eucrites have a 0.9 μm pyroxene absorption feature as deep as shown by Ibitira for example. However, these spectra are for "ideal" samples – all carefully prepared in the laboratory from igneous rocks. The surface of 4 Vesta

will be more complicated. All spectra are bidirectional spectra taken using identical measurement conditions on material ground to <25 μm. All spectra were collected by T. Hiroi and are publicly available from the Brown University Keck/NASA Reflectance Laboratory (http://www.planetary.brown.edu/relab/).

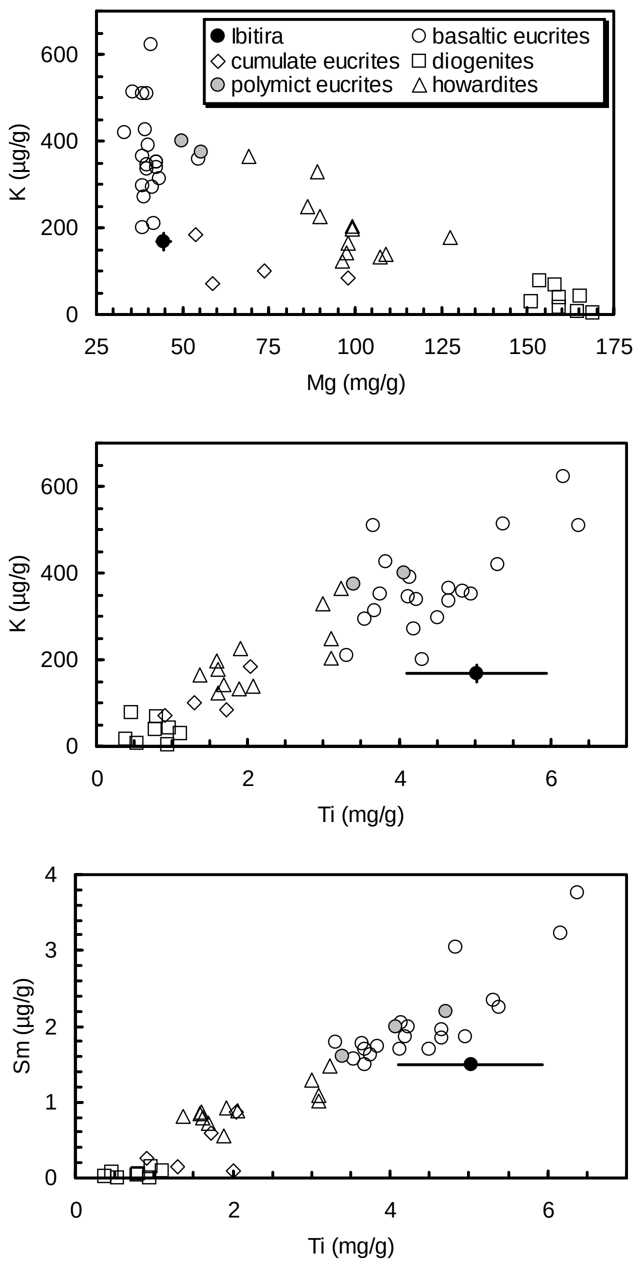
Figure 6. Comparison of the strength of the 0.9 μm pyroxene absorption feature in Relab spectra of Ibitira compared to HED meteorites. The width is the difference in wavelength between the shoulder in the spectrum on the long wavelength side of the absorption feature and the reflectance maximum on the short wavelength side. Min/max is a measure of the depth of the feature; the reflectance minimum/reflectance maximum in the 0.6-0.8 μm region.

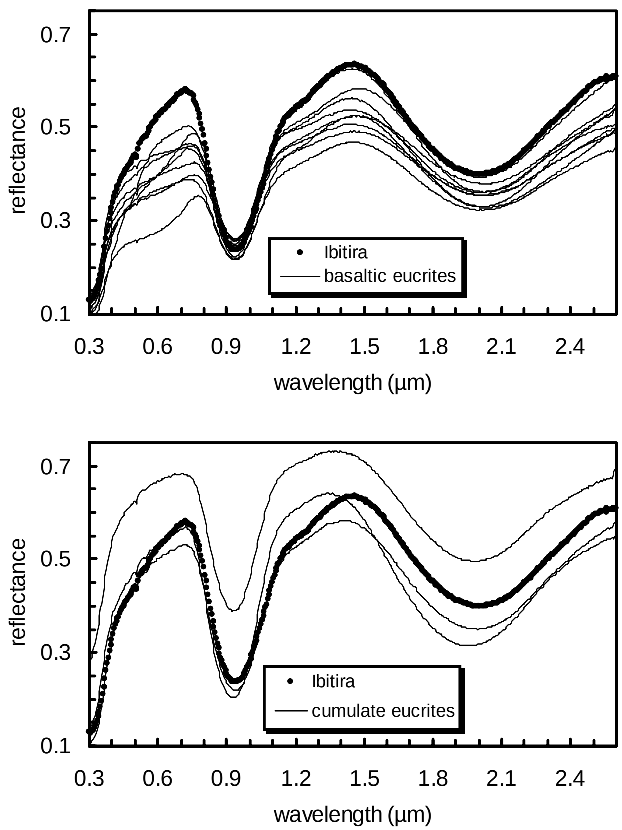

a.
Ibitira
HED
0.0
-0.1
-0.2
-0.3
3.0
3.5
4.0
4.5
$\Delta^{17}O'$ (‰)
$\delta^{18}O'$ (‰)
b.
P
C
basaltic eucrites
cumulate eucrites
diogenites
polymict eucrites
howardites
-0.17
-0.22
-0.27
3.0
3.5
4.0
4.5
$\Delta^{17}O'$ (‰)
$\delta^{18}O'$ (‰)

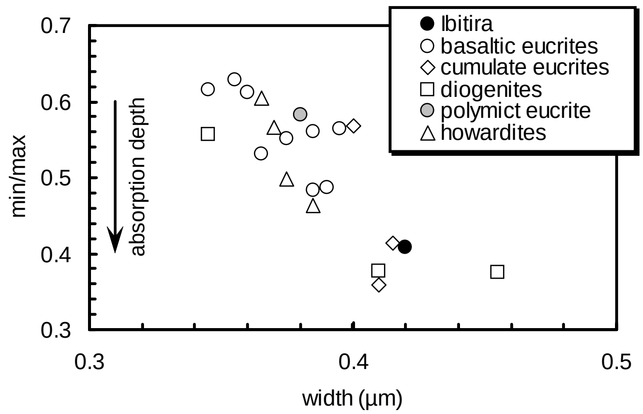

BTN 00300
EET 90020
GRA 98098
Sioux Co.
Stannern
Ibitira
a.
number of analyses
Fe/Mn (molar)
b.
Ibitira
basaltic eucrites
wo (mole %)
Fe/Mg (molar)
c.
Ibitira
basaltic eucrites
Fe/Mn (molar)
Y
Fe/Mg (molar)



1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.001
0.01
0.1
$(Ti/Hf)_{CI}$
$(Na/Ca)_{CI}$
Ibitira
basaltic eucrites
angrites
NWA 011
mesosiderite basalts


Ibitira
basaltic eucrites
cumulate eucrites
diogenites
polymict eucrites
howardites
K (µg/g)
Mg (mg/g)
0
200
400
600
25
50
75
100
125
150
175
K (µg/g)
Ti (mg/g)
0
200
400
600
0
2
4
6
Sm (µg/g)
Ti (mg/g)
0
1
2
3
4
0
2
4
6


0.7
0.5
0.3
0.1
reflectance
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
wavelength (µm)
Ibitira
basaltic eucrites
0.7
0.5
0.3
0.1
reflectance
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
wavelength (µm)
Ibitira
cumulate eucrites



Ibitira
basaltic eucrites
cumulate eucrites
diogenites
polymict eucrite
howardites
0.7
0.6
0.5
0.4
0.3
min/max
absorption depth
0.3
0.4
0.5
width (µm)

APPENDIXES

Table A1. Average Na, Ca, Ti and Hf data and Na/Ca and Ti/Hf ratios for the asteroidal basalts shown in Fig. 3.

meteorite	Na mg/g	Ca mg/g	Ti mg/g	Hf µg/g	Na/Ca CI-normalized	Ti/Hf CI-normalized
Ibitira	1.47	77.6	5.02	1.16	0.0343	1.131
basaltic eucrites						
A-881388	3.26	75.5	2.50	1.06	0.0782	0.616
ALHA81001	2.62	70.4	5.28	2.16	0.0674	0.639
Béréba	3.30	76.0	4.66	1.25	0.0786	0.974
Bouvante	3.56	74.2	6.13	2.72	0.0869	0.589
Cachari	3.84	75.2	3.83	1.11	0.0924	0.902
Caldera	3.49	71.4	3.54	0.92	0.0885	1.006
Camel Donga	3.84	72.4	4.66	1.43	0.0960	0.852
Chervony Kut	3.32	75.6	4.23	1.49	0.0795	0.742
Haraiya	3.15	71.5	3.28	1.02	0.0798	0.840
Jonzac	3.52	73.4	4.95	1.37	0.0868	0.944
Juvinas	3.17	76.2	3.75	1.20	0.0753	0.817
Lakangaon	3.85	74.1	5.38	1.60	0.0941	0.879
Millbillillie	3.38	73.5	4.15	1.14	0.0833	0.951
Nuevo Laredo	3.89	73.9	5.31	1.73	0.0953	0.802
Padvarninkai	3.18	74.0	3.68	1.34	0.0778	0.718
Palo Blanco Creek	3.15	75.4	4.13	1.15	0.0756	0.939
Pasamonte	3.84	74.9	4.13	1.45	0.0928	0.744
PCA 91007	3.52	72.8	4.40	1.49	0.0875	0.772
Piplia Kalan	3.63	74.4	4.50	1.26	0.0883	0.933
Pomozdino	3.48	71.4	4.83	2.21	0.0882	0.571
RKPA80204	3.05	71.0	4.60	1.30	0.0778	0.925
Sioux County	2.89	73.2	3.68	1.18	0.0715	0.815
Stannern	4.18	74.6	6.17	2.25	0.1014	0.717
Vetluga	3.38	71.3	4.20	1.39	0.0858	0.790
Y-791186	3.64	69.0	5.35	2.04	0.0955	0.685
Y-792510	3.38	74.2	4.45	1.37	0.0825	0.849
Y-793164	4.12	75.2	5.63	1.89	0.0992	0.779
Y-82037	2.89	75.3	2.80	0.97	0.0695	0.754
Y-82066	3.31	74.6	3.45	0.89	0.0803	1.013
angrites						
A-881371	0.16	81.2	5.30	1.03	0.0036	1.345
Angra dos Reis	0.25	165.2	13.10	2.31	0.0027	1.482
D'Orbigny	0.13	106.5	4.95	1.44	0.0022	0.898
LEW 86010	0.19	129.8	7.69	2.04	0.0027	0.985
LEW 87051	0.20	82.6	4.37	1.26	0.0044	0.906
Sahara 99555	0.12	108.0	5.50	1.80	0.0020	0.799
unique basaltic achondrite						
NWA 011	3.86	76.7	5.07	1.33	0.0911	0.996
mesosiderite primary basalt clasts						
Mount Padbury clast RV-05	3.27	68.1	4.30	0.88	0.0869	1.277
Vaca Muerta pebble 16	2.89	82.2	4.10	1.00	0.0636	1.072
Vaca Muerta clast 4677	2.30	64.3	4.40	0.79	0.0647	1.456
Vaca Muerta clast 4679	3.30	73.6	4.00	1.30	0.0812	0.804
Vaca Muerta clast 4695	3.20	71.3	3.10	1.19	0.0812	0.681

Table A2. Listing of data sources used to calculate meteorite averages.

Authors	Year	Journal	Notes
Allen & Mason	1973	GCA 37:1435	GCA = Geochim. Cosmochim. Acta
Barrat et al.	2000	MAPS 35:1087	MAPS = Meteoritics & Planetary Science
Binns	1977	unpublished	
Blanchard	1981	BVSP A-11:70	BVSP = Basaltic Volcanism Study Project (book)
Boctor et al.	1994	M 29:445	M = Meteoritics
Bogard & Garrison	1995	GCA 59:4317	
Bogard & Garrison	2003	MAPS 38:669	
Bogard et al.	1985	GCA 49:941	
Buchanan	-	unpublished	
Buchanan et al.	2000	MAPS 35:609	
Christophe Michel-Levy et al.	1987	BM 110:449	BM = Bull. Mineral.
Cleverly et al.	1986	M 21:263	
Delaney et al.	1984	LPS XV:212	LPS = Lunar Planet. Sci.
Dickenson et al.	1985	CE 44:245	CE = Chemie der Erde
Duke & Silver	1967	GCA 31:1637	
Easton & Lovering	1964	ACA 30:543	ACA = Analytica Chimica Acta
Edwards	1955	GCA 8:285	
Edwards & Urey	1955	GCA 7:154	
Ehmann et al.	1979	ODE 2:247	ODE = Origin & Distribution of the Elements (book)
Fredriksson & Kraut	1967	GCA 31:1701	
Fukuoka	1990	ASAM 15:155	ASAM = Abst. Symp. Antarctic Meteorites
Gast	1962	GCA 26:927	
Gast et al.	1970	PLSC 1:1143	PLSC = Proc. Lunar Sci. Conf.
Higuchi & Morgan	1975	PLSC 6:1625	
Jarosewich	1990	M 25:323	
Jerome	1970	Ph.D. U of Oregon	
Jochum et al.	1980	M 15:31	
Jochum et al.	2000	MAPS 35:229	
Kharitonova & Barsukova	1982	RM 40:41	
Kiesl et al.	1967	MFC 98:972	MFC = Monatshefte für Chemie
Kimura et al.	1991	PNSAM 4:263	PNSAM = Proc. NIPR Symp. Antarctic Met.
Kolesov & Hernandez	1984	RM 43:106	
Korotchantseva et al.	2003	LPS XXXIV:1575	
Kurat et al.	2004	GCA 68:1901	
Kvasha & Dyakonova	1972	RM 31:109	RM = Meteoritika (Russian)
Lee & Halliday	1997	N 388:854	N = Nature
Lodders	2003	AJ 591:1220	AJ = Astrophys. J.
Ma et al.	1977	EPSL 35:331	
Mason	1983	AMNL 6,1:1	AMNL = Antarctic Meteorite Newsletter
Mason et al.	1979	SCES 22:45p.	SCES = Smithsonian Contrib Earth Sci
McCarthy et al.	1973	EPSL 18:433	EPSL = Earth Planet. Sci. Lett.
McCarthy et al.	1974	M 9:215	
McKay et al.	1988	LPS XIX:762	
Metzler et al.	1995	PSS 43:499	PSS = Planetary & Space Science

Table A2 (continued). Listing of data sources used to calculate meteorite averages.

Authors	Year	Journal	Notes
Mittlefehldt	1979	GCA 43:1917	
Mittlefehldt	-	unpublished	
Mittlefehldt & Lindstrom	1990	GCA 54:3209	
Mittlefehldt & Lindstrom	1993	PNSAM 6:268	
Mittlefehldt & Lindstrom	2003	GCA 67:1911	
Mittlefehldt et al.	2002	MAPS 37:345	
Miura et al.	1993	GCA 57:1857	
Morrison	1971	AAGC:51	AAGC = Activation Anal in Geochem & Cosmochem (book)
Palme & Rammensee	1981	PLPSC 12:949	
Palme et al.	1978	PLPSC 9:25	PLPSC = Proc. Lunar Planet. Sci. Conf.
Palme et al.	1988	M 23:49	
Patchett & Tatsumoto	1980	N 288:571	
Podosek & Huneke	1973	GCA 37:667	
Prinz et al.	1990	LPS XXI:979	
Quitté et al.	2000	EPSL 184:83	
Rieder & Wänke	1969	MR:75	MR = Meteorite Research (book)
Rubin & Mittlefehldt	1992	GCA 56:827	
Schaudy et al.	1967	CG 2:279	CG = Chemical Geology
Schmitt et al.	1972	M 7:131	
Shima	1979	GCA 43:353	
Shukla et al.	1997	MAPS 32:611	
Stolper	1977	GCA 41:587	
Tatsumoto et al.	1981	PSAM 6:237	PSAM = Proc. Symp. Antarctic Meteorites
Tera et al.	1970	PLSC 1:1637	
Urey & Craig	1953	GCA 4:36	
von Michaelis et al.	1969	EPSL 5:387	
Wänke & Konig	1959	ZN 14a:860	ZN = Zeitschrift für Naturwissenshaften
Wänke et al.	1972	PLSC 3:1251	
Wänke et al.	1974	PLSC 5:1307	
Wänke et al.	1977	PLSC 8:2191	
Warren & Jerde	1987	GCA 51:713	
Warren et al.	1990	PLPSC 20:281	
Warren et al.	1995	ASAM 20:261	
Warren et al.	1996	ASAM 21:195	
Weyer et al.	2002	CG 187:295	
Yamaguchi et al.	2002	S 296:334	S = Science
Yanai & Kojima	1995	CAM	CAM = Catalog of the Antarctic Meteorites
Yin et al.	2002	N 418:949	